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Heterogeneity and assessment uncertainties in forest characteristics and biomass carbon stocks: Important considerations for climate mitigation policies

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ABSTRACT

The management of forests to store carbon and mitigate climate change has received significant international attention during the last decade. Using *in situ* data from a 2008–2009 forest inventory field campaign in Sri Lanka, this study describes the structural characteristics and carbon stocks of six natural forest types. This paper has a dual scope: i) to highlight the variation in carbon stored in aboveground biomass within and between forest types and ii) to determine the implications of the allometric equations chosen to calculate biomass carbon stocks. This study concerns work related to climate change interventions, such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) and other forest-related, performance-based initiatives that require proper monitoring, reporting, and verification of carbon stocks, sinks and emissions. The results revealed that forests are heterogeneous in terms of tree density and height–diameter relationships, both between and within the six forest types investigated. The mean aboveground carbon stock in the different forest types ranged from 22 to 181 $\mathrm{Mg\,C\,ha^{-1}}$, and there were statistically significant differences in the carbon stocks of the six forest types in 7 of 15 cases. The estimated carbon stock depended heavily on the allometric equation used for the calculations, the variables, and its application to the specific life zone. Due to the diversity of forest structures, these results suggest that caution should be taken when applying default values to estimate forest carbon stocks and emission values in reporting and accounting schemes. The results also indicated the need for allometric equations that are context-specific for different forest types. Therefore, new field investigations and measurements are needed to determine these specific allometric equations, as well as the potential variation in forest carbon stocks in tropical natural forests.

1. Introduction

Globally, forests store and sequester the majority of living terrestrial biomass (net sink of 1.1 ± 0.8 Pg C per year) (Pan et al., 2011), and provide important ecosystem services (Hansen et al., 2013; Tyukavina et al., 2015). Tropical forests are generally more effective at carbon (C) sequestration than other forest ecosystems due to their high net primary production (Cleveland et al., 2015). Aboveground biomass (AGB) is a useful proxy for the evaluation of forest carbon stocks. However, several environmental and bioclimatic factors can affect AGB accumulation and its translation into carbon stock, including soil type, soil fertility, climatic variation, successional stage, topography, landscape scale, geological substrate, species composition, tree density, and human disturbance levels (Asner et al., 2010; Saatchi et al., 2011; Berenguer et al., 2014). Due to our limited understanding of the nature of carbon stocks in forest ecosystems (Tan et al., 2013), which is obvious in the scarce data regarding the spatial variation of the factors listed above, particularly for the tropics, it is difficult to generalize about AGB over regional or landscape scales (Saatchi et al., 2011; Baccini et al., 2012). This is a barrier to reliable reporting of forest carbon stocks for organisations such as the Food and Agriculture Organization of the United Nations (FAO), which is responsible for the Forest Resource Assessment (FRA), for the creation of climate mit-

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igation schemes, such as Reducing Emissions from Deforestation and Forest Degradation (REDD+), and to the achievement of climate goals stated in the Intended Nationally Determined Contributions (INDCs). Thus, the uncertainties associated with the assessment of forest carbon stocks is a serious concern for policy development and implementation.

Estimating the carbon stock in forest AGB using non-destructive means requires the use of biomass allometric calculations. The high species richness in tropical forests makes it unreasonable to use species-specific regression equations. Therefore, a range of pan-tropical allometric equations have been developed for mixed tree species in various forest types and bioclimatic zones that use a variety of variables and algebraic forms (Brown, 1997; Chave et al., 2005). However, selecting which equations to apply to new situations across varying environmental conditions is challenging because the results may differ by more than a factor of two depending on the equations applied to a specific dataset (Hairiah et al., 2001). Earlier studies have varied in their suggestions for using these allometric equations, specifically in terms of which variables to use. Generally, the diameter at breast height (DBH) for trees is used either as a single variable or in combination with tree height and other data (Brown, 1997, 2002). Chave et al. (2005, 2014) and Henry et al. (2010) also emphasized that wood density is a main variable needed to correctly estimate forest AGB. Relationships between variables, such as height and diameter, can also vary by region and forest type, which make estimations of AGB subject to bias if only the DBH is measured, and allometric differences are ignored (Feldpausch et al., 2011, 2012; Vieilledent et al., 2011). Additionally, many of the pan-tropical allometric equations for mixed tree species take into account environmental variables and have been developed for dry, moist, and wet forest types following the Holdridge life zone system (Holdridge, 1967; Brown et al., 1989).

The management of forests to store carbon and mitigate climate change has received significant international attention in recent years. Reducing deforestation and forest degradation through forest conservation, forest enhancement, and sustainable forest management, which are covered in REDD+, have been frequently discussed in the United Nations climate change negotiations (Gibbs et al., 2007; Angelsen et al., 2012; Sills et al., 2014) and identified by professional and academic institutions (Visseren-Hamakers et al., 2012; Minang and van Noordwijk, 2013). In the proposed REDD+ guidelines, developed countries should provide incentives and financial compensation to developing countries for climate change mitigation benefits and to maintain and enhance forest carbon stocks.

Sri Lanka's natural forests are rich in endemic species of flora and fauna and are critical for soil conservation and flood control. The conservation, protection and sustainable management of these forests has motivated Sri Lanka to engage in REDD+ activities through the UN-REDD program (UN-REDD, 2012). Sri Lanka's UN-REDD National program started in 2013 with the aim to develop and implement a national REDD+ strategy, including the recent south–south knowledge exchanges regarding forest monitoring and community-based REDD+ pilots (UN-REDD, 2015a). Sri Lanka also targets forest conservation as a carbon mitigation option and plans to increase the total forest cover in the country from 29.6% to 32% by 2030, as indicated in the Intended Nationally Determined Contributions (INDC) submitted the United Nations Framework Convention on Climate Change (UNFCCC) (Government of Sri Lanka, 2016).

Although information about the productivity and carbon stocks in the AGB of various Sri Lankan plantation forests is available (e.g., Costa and Suranga, 2012), there is less information available about the physiographic characteristics of natural forests and no studies have recently assessed the biomass carbon stocks of natural forests on a national level (UN-REDD, 2012). Thus, more complete and higher quality information is needed about the spatial distribution of carbon stock dynamics across multiple forest types in Sri Lanka. Such information would also facilitate sustainable forest management, identify the forest types and regions with rich carbon stocks and increase the collection of information needed to implement policies and measures to mitigate and adapt to climate change. In addition, the lack of a standard approach (Chave et al., 2005; Bryan et al., 2010) for estimating forest carbon stocks can result in large estimate ranges and uncertainties. This variability needs to be addressed for improved FAO reporting and REDD+ implementation and is investigated here using *in situ* data from Sri Lanka.

The specific objectives of the study were to assess the structural characteristics of tree density, the tree height and diameter relationship, tree diameter size and the basal area variation of trees and forest types, to determine the variation in the aboveground biomass carbon within and between various natural forest types, to limit the uncertainties associated with estimations of carbon stocks using pan-tropical allometric equations, and identify the potential policy implications associated with the forest inventory data related to carbon and climate change.

2. Materials and methods

2.1. Study area

Sri Lanka has a tropical climate characterized by two major monsoon periods: the southwest monsoon from May to September and the northeast monsoon from December to February. A large region in the south-central part of the country is 1500 m above sea level (m.a.s.l.), however, most of the country consists of a large coastal plain below 500 m.a.s.l. where most forests and agricultural regions are located (Government of Sri Lanka, 2012). Despite Sri Lanka's relatively small land area of 6.5 million hectares (ha), large variations in rainfall, altitude, and soil characteristics have created a striking variety of forest types, ranging from wet evergreen to montane forests and vast areas of dry monsoon forests with very high species diversity and many endemics. A long history of colonial rule, civil war, and a growing population has heavily fragmented the once widespread forest area on the island, and natural forest cover has declined from 80%, roughly 5.3 million hectares (Mha), in 1880–27%, roughly 1.8 Mha, in 2015 (FAO, 2015). Most of the natural forest cover in Sri Lanka, approximately 86%, is located in dry and intermediate zones. 8% and 10% of the forest area is designated as primary forest and plantation forest, respectively, and 82% of the total forest area is classified as naturally regenerated forest in which there are clear indications of human activities (ibid.). Estimates have shown that the forest cover is still declining at approximately 0.3% per year (2010–2015), although this is a slower rate than in the past (1.3% per year between 1990 and 2000) (FAO, 2015).

This study was conducted in central and southern Sri Lanka in the districts of Badulla, Moneragala, Ratnapura, Nuwara Eliya, Kandy, Matale, Kurunegala, and Anuradhapura during 2008 and 2009. The study area covers all of Sri Lanka's ecological zones; dry (1250–1525 mm precipitation per year), intermediate (1526–2280 mm per year), and wet (2281–5100 mm per year) (Fig. 1). The temperature differences in the study areas depend mainly on differences in elevation, with a mean annual temperature of 26–28 °C in the coastal plains and 15–19 °C in the mountainous, upcountry region (Government of Sri Lanka, 2012). The natural forest types measured include lowlands ($n = 97$, primarily in the Sinharaja Forest Reserve), sub-montane ($n = 10$), moist monsoon ($n = 10$), dry monsoon ($n = 16$), montane ($n = 24$), and open ($n = 35$) forests. Open forests were defined as all forested land with a canopy